

A propelling neutron star in the enigmatic Be-star γ Cassiopeia

K. Postnov^{*1}★, L. Oskina², J.M. Torrejón³

¹ Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Universitetskij pr., 13, Moscow 119234, Russia

² Institute for Physics and Astronomy, University Potsdam, 14476 Potsdam, Germany

³ Instituto Universitario de Física Aplicada a las Ciencias y las Tecnologías, Universidad de Alicante, 03690 Alicante, Spain

Received ... Accepted ...

ABSTRACT

The enigmatic X-ray emission from the bright optical star, γ Cassiopeia, is a long-standing problem. γ Cas is known to be a binary system consisting of a Be-type star and a low-mass ($M \sim 1 M_{\odot}$) companion of unknown nature orbiting in the Be-disk plane. Here we apply the quasi-spherical accretion theory onto a compact magnetized star and show that if the low-mass companion of γ Cas is a fast spinning neutron star, the key observational signatures of γ Cas are remarkably well reproduced. Direct accretion onto this fast rotating neutron star is impeded by the propeller mechanism. In this case, around the neutron star magnetosphere a hot shell is formed that emits thermal X-rays in qualitative and quantitative agreement with observed properties of the X-ray emission from γ Cas. We suggest that γ Cas and its analogs constitute a new subclass of Be-type X-ray binaries hosting rapidly rotating neutron stars formed in supernova explosions with small kicks. The subsequent evolutionary stage of γ Cas and its analogs should be the X Per-type binaries comprising low-luminosity slowly rotating X-ray pulsars. The model explains the enigmatic X-ray emission from γ Cas, and also establishes evolutionary connections between various types of rotating magnetized neutron stars in Be-binaries.

Key words: accretion, stars: emission-line, Be, stars: neutron

1 INTRODUCTION

The optically brightest Be-star γ Cas (B0.5IVpe) is well seen in the night sky by the naked eye even in a big city. It is a well known binary system that consists of an optical star with mass $M_{\text{Be}} \approx 16 M_{\odot}$ and an unseen hot companion with mass $M_X \approx 1 M_{\odot}$. The binary orbital plane and the disk of the Be-star are coplanar (Harmanec et al. 2000; Miroshnichenko et al. 2002; Gies et al. 2007). Since the discovery of X-ray emission from γ Cas 50 years ago (Mason et al. 1976), its enigmatic properties attracted large attention, but so far have remained unexplained (see recent review by Smith et al. 2016).

γ Cas is a prototype of a class of Be-stars that have X-ray luminosities of $10^{32} - 10^{33} \text{ erg s}^{-1}$, which is intermediate between those usually observed from B-stars with similar spectral types and those of X-ray and cataclysmic variable binaries. The defining feature of X-ray emission from the class of γ Cas analogs is a very hot thermal spectrum with $T \gtrsim 100 \text{ MK}$ (or $kT \gtrsim 10 \text{ keV}$) and the presence of fluorescent FeK-line. No X-ray pulsations have been detected in γ Cas analogs.

After γ Cas was detected in X-rays, the idea of an accreting neutron star (NS) companion had been put forward (White et al. 1982) based on the apparent similarity between the X-ray spectra of γ Cas and the Be X-ray binary (BeXRB) X Per that hosts

a NS. However, the subsequent accumulation and analysis of high-quality multiwavelength observations of γ Cas revealed major difficulties for this model. For example, Lopes de Oliveira et al. (2006) pointed out that direct accretion onto a NS is unlikely because the observed X-ray luminosity of γ Cas (B0.5IVe+NS?, $P_{\text{orb}} \approx 204 \text{ day}$, $e \lesssim 0.03$) would be much lower than in X Per (O9.5III-IVe+NS, $P_{\text{orb}} \approx 250 \text{ day}$, $e \approx 0.1$). It was also pointed out that the FeK-line is usually not seen in the X-ray spectra of long-period BeXRBs while it is observed in γ Cas. Moreover, a non-thermal spectral component is typically present in X-ray spectra of BeXRBs, but is absent in γ Cas. Lopes de Oliveira et al. (2006) considered the possibility of an unusual accretion regime for a NS, such as accretion onto the NS magnetosphere, and concluded that this is unlikely as well. Besides the NS hypothesis, at least two other scenarios about the nature of the γ Cas and its analogs have been discussed in the literature – accretion onto a white dwarf and magnetic star-disk interaction. We will discuss these alternative scenarios in Section 9.

Despite large discussion in the literature, to our knowledge no quantitative model predicting the observed properties of γ Cas exists so far. In this paper we endeavor to develop such model. We derive quantitative predictions of X-ray emission from a NS in the propeller regime embedded in a hot quasi-spherical shell and compare them with observed properties of γ Cas.

The good agreement between our model and observations lends credence to the proposed model and allows us to suggest an

* E-mail: pk@sai.msu.ru

evolutionary scenario for γ Cas and its analogs. In our new scenario these objects represent natural evolutionary stage of binary X-ray systems that experienced mass exchange in the past, suffered only a small kick during supernova (SN) explosion of the primary, and will evolve to accreting BeXRBs, such as X Per, in the future.

The formation of X Per in the context of the standard evolutionary scenario for BeXRBs was considered by [Delgado-Martí et al. \(2001\)](#). They found that the formation of this Be+NS system likely involved a quasi-stable and nearly conservative transfer of mass from the primary to the secondary. It was suggested that the final mass of He star remnant of the primary was less than $6 M_\odot$ and suggested that its supernova explosion might have been completely symmetric. Using a Monte Carlo study of natal kicks, [Delgado-Martí et al. \(2001\)](#) speculated that there may be a substantial population of neutron stars formed with little or no kick. [Shtykovskiy & Gilfanov \(2005\)](#) studied the population of compact X-ray sources in the Large Magellanic Cloud, and included the propeller effect to explain the observed X-ray luminosity distribution.

In this paper we expand the standard approach to the high-mass X-ray binary evolution (e.g. [Pfahl et al. 2002](#)) by showing that the quasi-spherical accretion in young BeXRBs may be impeded. Our model can have important implications for the physics of supernova in massive binary systems and for the formation of double neutron star systems in the Galaxy.

The paper is organized as follows: the basic principles of the propeller effect at quasi-spherical wind stage are introduced in Section 2. The properties of a hot magnetospheric shell are derived in Section 3. The evolution of the neutron star spin is considered in Section 4, and its energy balance is estimated in Section 5. A brief summary of the model predictions is given in Section 6, and a comparison of the model with observations of γ Cas is made in Section 7. The evolutionary scenario for γ Cas-class of objects is discussed in Section 8. The discussion and conclusion are in Section 9.

2 PROPELLER EFFECT

Neutron stars are born in core collapses of massive stars. NSs have masses of $0.8 M_\odot \leq M_X \leq 2.5 M_\odot$ ([Lattimer & Prakash 2007](#)), initially short spin periods $P_0^* \sim 10 - 100$ ms, and are strongly magnetized with the characteristic dipole magnetic moment $\mu_{30} = \mu / (10^{30} \text{ G cm}^3) \sim 1$ (e.g. [Popov & Turolla 2012](#)).

Some NSs are found in binary systems with a high-mass stellar companion of OB or Be spectral type. The OB-stars lose mass via their radiatively driven winds, and rapidly rotating Be-stars also possess accretion disks ([Porter & Rivinius 2003; Reig 2011](#)). In the standard formation model of high-mass X-ray binaries, a NS gravitationally attracts the wind matter outflowing from its early-type companion within the Bondi radius

$$R_B = 2GM_X/v_0^2, \quad (1)$$

where v_0 is the NS velocity relative to the wind ([van den Heuvel & Heise 1972; Tutukov et al. 1973](#)). If the specific angular momentum of the gravitationally captured matter is small, the accretion flow is quasi-spherical. A NS with radius $R_0 \approx 10^6$ cm and accreting matter with density ρ at the rate $\dot{M}_B \approx \pi \rho v_0 R_B^2$ could gravitationally sustain a luminosity $GMM_B/R_0 \sim 0.1 \dot{M}_B c^2$ (where c is the speed of light) ([Bondi & Hoyle 1944](#)). Hence, if all gravitationally captured matter were able to reach the NS surface, a bright X-ray source would appear.

However, for matter to reach the NS surface, it should penetrate through its magnetosphere with the characteristic radius $R_A \sim 10^8 - 10^9$ cm, defined by the pressure balance between the ambient matter and the magnetic field (see Eq. 7). Besides the magnetospheric barrier, the centrifugal barrier can also prevent the matter accretion. The rigidly rotating NS magnetosphere reaches a Keplerian velocity at the distance $R_c = (GM(P^*)^2/4\pi^2)^{1/3}$, where P^* is the NS spin period. Only when the condition $R_c \leq R_A$ is met the accretion can start. The corresponding NS spin period is then $P_A^* \approx 17(R_A/10^9 \text{ cm})^{3/2}$ s. If $R_A > R_c$ or, equivalently, $P^* < P_A$, the centrifugal barrier at the magnetospheric boundary would prevent matter accretion ([Illarionov & Sunyaev 1975; Stella et al. 1986](#)). Such situation is referred to as a ‘propeller stage’.

The propeller effect has been suggested to operate at low states of transient X-ray pulsars ([Tsygankov et al. 2016b; Lutovinov et al. 2016; Tsygankov et al. 2016a](#)) and has been invoked to explain non-stationary behaviour of supergiant fast X-ray transients ([Grebenev & Sunyaev 2007; Bozzo et al. 2008](#)).

3 THE HOT MAGNETOSPHERIC SHELL AND ITS PROPERTIES

In a wind-fed binary system with rapidly rotating NS, the propeller effect has an important difference compared to the one operating in the disk-fed systems. At the propeller stage, the gravitationally captured material from the stellar wind of the companion will accumulate above R_A to form a hot quasi-spherical shell extending up to $\sim R_B$ ([Davies & Pringle 1981; Shakura et al. 2012](#)). The shell can power a gravitational luminosity of

$$L_X \approx GM_X \dot{M}_B / R_A \sim 10^{32} \text{ erg s}^{-1}. \quad (2)$$

To good approximation, the density and temperature distributions in the shell can be found from the hydrostatic equilibrium:

$$\rho(R) = \rho_A (R_A/R)^{3/2}, \quad T(R) = T_A (R_A/R) \quad (3)$$

where ρ_A and T_A are referred to the near magnetospheric values. The temperature is determined by the condition

$$\mathcal{RT} = \mu_m \frac{\gamma - 1}{\gamma} GM_X \frac{1}{R_A}, \quad (4)$$

where \mathcal{R} is the universal gas constant, μ_m is the molecular weight and γ is adiabatic index of the gas. In the following we will assume $\mu_m = 0.5$ and $\gamma = 5/3$. The magnetospheric radius is determined from the pressure balance at the magnetospheric boundary:

$$K_2 (B_0^2/8\pi)(R_0/R_A)^6 = \rho_A \mathcal{RT}_A = \rho_A (2/5)(GM_X/R_A), \quad (5)$$

where the factor $K_2 \approx 7.56$ takes into account compression of a quasi-spherical magnetosphere ([Arons & Lea 1976](#)). The total X-ray luminosity of the shell due to bremsstrahlung cooling is

$$L_X = \int_{R_A}^{R_B} \epsilon_{\text{br}} 4\pi r^2 dr = \frac{4\pi K_{\text{br}}}{\sqrt{\mathcal{R}}} \rho_A^2 \sqrt{\frac{2}{5}} \frac{GM_X}{R_A} \frac{R_A^3}{2} \left(1 - \frac{1}{\sqrt{R_B/R_A}}\right), \quad (6)$$

where we have used $\epsilon_{\text{br}} = K_{\text{br}} \rho^2 \sqrt{T}$ and the scaling laws for the density and temperature in the shell given by Eq. (3). The last term in the parentheses can be neglected since usually $R_B/R_A \gg 1$. For a given L_X and NS magnetic field $\mu = B_0 R_0^3/2$, equations (5) and (6) can be solved to give

$$R_A \approx 7.6 \times 10^8 \text{ cm} \mu_{30}^{8/15} L_{32}^{-2/15} (M_X/M_\odot)^{-4/15}, \quad (7)$$

where $L_{32} = L_X/(10^{32} \text{ erg s}^{-1})$, and

$$\rho_A \approx 4.4 \times 10^{-11} [\text{g cm}^{-3}] (L_{32}/\mu_{30})^{2/3} (M_X/M_\odot)^{1/3}, \quad (8)$$

and the electron number density:

$$n_{e,A} \approx 2.6 \times 10^{13} [\text{cm}^{-3}] (L_{32}/\mu_{30})^{2/3} (M_X/M_\odot)^{1/3}. \quad (9)$$

The temperature at the shell base is

$$\begin{aligned} T_A &= \frac{2}{5} \frac{GM_X}{R_A} \approx 27 [\text{keV}] (R/10^9 [\text{cm}])^{-1} \\ &\approx 36 [\text{keV}] \mu_{30}^{-8/15} L_{32}^{2/15} (M_X/M_\odot)^{19/15}. \end{aligned} \quad (10)$$

This high temperature justifies the use of bremsstrahlung radiative losses from the shell.

The volume emission measure of the shell is given by

$$\begin{aligned} \text{EM} &= \int_{R_A}^{R_B} n_e^2(r) 4\pi r^2 dr = 4\pi n_{e,A}^2 R_A^3 \ln\left(\frac{R_B}{R_A}\right) \\ &\approx 3.7 \times 10^{54} [\text{cm}^{-3}] \mu_{30}^{4/15} L_{32}^{14/15} (M_X/M_\odot)^{-2/15} \ln\left(\frac{R_B}{R_A}\right). \end{aligned} \quad (11)$$

In the context of a NS coplanar with the Be-star disk, given the slow equatorial disk wind velocities $v_0 \sim 10^7 \text{ cm s}^{-1}$, we find $R_B/R_A \sim 100$ (see Eq. 1), and the EM can be $\sim 10^{55} [\text{cm}^{-3}]$ and even higher.

4 EVOLUTION OF THE NEUTRON STAR SPIN

The propeller effect can be important in astrophysical context provided that its duration is sufficiently long compared to the life time of the Be-star (several million years). The propeller effect operates only for fast rotating NSs. Therefore, to evaluate for how long accretion may be inhibited and a hot magnetospheric shell can be supported by the wind from the optical star, one should consider the spin evolution of a non-accreting NS.

The transfer of angular momentum in magnetospheric shells around quasi-spherically accreting NSs was considered in more detail by Shakura et al. (2012). It was found, in particular, that in such shells a nearly iso-momentum angular velocity distribution is established, $\omega(R) = \omega_m(R_A/R)^2$, where ω_m is angular velocity of matter at the magnetosphere. However, when accretion onto the NS is centrifugally prohibited, the angular momentum transport by viscous forces through the surrounding convective shell leads to the angular velocity distribution $\omega(R) = \omega_m(R_A/R)^{7/4}$ (see Appendix A6 Shakura et al. 2012)).

From Eq. (51) and (52) presented in Shakura et al. (2012), at the stage with no accretion, the braking torque applied to NS from the surrounding shell is

$$I\dot{\omega}_* = -\frac{49}{4} \omega_B^2 \left(\frac{R_B}{R_A}\right)^{7/2} \pi C \rho_A R_A^5, \quad (12)$$

where I is the NS moment of inertia, $\omega_B = 2\pi/P_{\text{orb}}$ is the binary orbital frequency, $C \gtrsim 1$ is a numerical coefficient that determines turbulent viscosity through the Prandtl law and hence viscous stresses in the convective shell. Plugging into (12) the density distribution in the shell, $\rho_A = \rho_B(R_B/R_A)^{3/2}$, as given by (8) and expressing it through the X-ray luminosity L_X , Eq. (12) for the braking torque can be rearranged to

$$I\dot{\omega}_* = -49\omega_B^2 R_B^3 C \left(\frac{R_A L_X}{GM_X v_0}\right). \quad (13)$$

The characteristic NS spin-down time in this regime thus becomes:

$$\begin{aligned} t_{\text{sd}} \equiv \frac{I\omega_*}{I\dot{\omega}_*} &= \frac{I\omega_*}{49\omega_B^2 R_B^3 C} \left(\frac{GM_X v_0}{R_A L_X}\right) \\ &\approx 2 \times 10^5 [\text{yr}] \left(\frac{P_*}{1\text{s}}\right)^{-1} \left(\frac{P_{\text{orb}}}{100\text{d}}\right)^2 \left(\frac{v_0}{100\text{km s}^{-1}}\right)^7 \left(\frac{R_A}{10^9\text{cm}}\right)^{-1} L_{32}^{-1}, \end{aligned} \quad (14)$$

(here the constant C was set to unity.)

As can be seen from Eq. (14), the NS spin-down time is extremely sensitive to the NS velocity relative to the disk wind (as $\sim v_0^7$) and to binary orbital period (as $\sim P_{\text{orb}}^2$). It can be made much longer than the characteristic spin-down time at the propeller stage during the disk accretion onto NS with the same magnetospheric radius, $t_{\text{sd,d}} \approx (I\omega_*)(\mu^2/R_A^3)^{-1} \sim 10^5 [\text{yr}] (P_*/1\text{s})^{-1} \mu_{30}^{-2} R_{A,9}^3$.

Given the significant time duration estimated by Eq. (14), it is obvious that propelling NSs surrounded by hot quasi-spherical shells can be present among low-luminosity non-pulsating high-mass X-ray binaries. Their X-ray spectral properties as summarized below in Section 6 and their long orbital binary periods can be used to distinguish them from, for example, faint hard X-ray emission from magnetic cataclysmic variables (e.g. Hong et al. 2016).

5 HEATING OF THE MAGNETOSPHERIC SHELL

In the case of a ‘supersonic propeller’ (Davies & Pringle 1981), additional source of the shell heating is provided by the mechanical energy flux from the spinning-down NS (sometimes referred to as ‘magnetospheric accretion’, see Stella et al. 1986). Multiplication of Eq. (12) by the angular velocity difference at the magnetospheric boundary, $(\omega_* - \omega_m)$, gives the influx of the mechanical energy into the shell at the propeller stage. Clearly, once $\omega_m \rightarrow \omega_*$ during the NS spin-down, the mechanical energy supply to the shell should vanish. However, even in this case the shell can be kept hot due to the gravitational energy release given by Eq. (2).

To provide X-ray luminosity at the level $L_X \sim 10^{32} - 10^{33} \text{ erg s}^{-1}$ and assuming $R_A \sim 10^9 \text{ cm}$, the gravitational capture rate of stellar wind matter must be $\dot{M}_B \sim 10^{15} - 10^{16} \text{ g s}^{-1}$ or $10^{-10} - 10^{-11} M_\odot \text{ yr}^{-1}$. Using Eqs. (3) and (8), it can be shown that the wind density at the outer boundary of the shell near R_B is sufficient to provide the required mass accretion rate.

The above estimates are done using simple spherically symmetric considerations, which may be violated in complex regions near R_B . However, it is important to note that the observed X-ray luminosity is mostly determined by the Bondi-Hoyle rate, $\dot{M}_B \sim \rho_B R_B^2 v_0$. Expressing it through the density near the shell base eliminates the ill-known value of the wind velocity:

$$\begin{aligned} \dot{M}_B &\sim (1/4)\pi\rho_B R_B^2 v_0 \approx (1/4)\pi\rho_A R_A^{3/2} R_B^{1/2} v_0 \\ &\approx 6 \times 10^{15} [\text{g s}^{-1}] \mu_{30}^{2/15} L_{32}^{4/5} (M_{\text{NS}}/M_\odot)^{-2/5} \end{aligned} \quad (15)$$

(here the factor 1/4 takes into account density jump in the strong shock near R_B). Thus, our basic considerations should not be strongly affected by the complicated flow details at R_B and provide robust first-order estimates.

The radiation cooling time of the hot plasma near the base of the shell is rather short, $t_{\text{cool}} \sim 2 \times 10^{11} [\text{s}] T^{1/2} n_e^{-1} \sim 1000 \text{ s}$. The temperature gradient in the quasi-spherical shell turns out to be superadiabatic (Shakura et al. 2012), indicating the presence of convection. To avoid rapid cooling, the convection should lift up a hot parcel of gas faster than it radiatively cools down, i.e. the condition $t_{\text{cool}} > t_{\text{conv}}$, where $t_{\text{conv}} = R_A/v_{\text{conv}}$ is the characteristic time of convective overturn near the shell base, should be met.

The convective velocity is $v_{\text{conv}} = \epsilon_c c_s$, where $c_s = \gamma RT$ is the adiabatic sound velocity, $\epsilon_c \leq 1$. Plugging R_A and T_A from Eq. (7) and Eq. (10), we obtain for the condition $t_{\text{cool}} > t_{\text{conv}}$

$$(\mu_{30} L_{32})^{2/5} < 115 \epsilon_c (M_X/M_\odot)^{28/15}, \quad (16)$$

which is easily satisfied even for small convective velocities. Convection initiates turbulence, and the hot thermal plasma in the

quasi-spherical shells around NS magnetospheres should show signs of turbulent velocities with $v_{\text{turb}} \sim v_{\text{conv}} \sim 1000 \text{ km s}^{-1}$.

6 BRIEF SUMMARY OF THE MODEL PREDICTIONS

Lets us summarize the basic properties of the hot magnetospheric shell supported by a propelling NS in circular orbit in a binary system around a Be-star. The model predicts the following observables:

- i) the system emits optically thin multi-temperature thermal radiation with the characteristic temperatures above $\sim 10 \text{ keV}$, high plasma densities $\sim 10^{13} \text{ cm}^{-3}$ and emission measures $\sim 10^{55} \text{ cm}^{-3}$;
- ii) the typical X-ray luminosity of the system is $\sim 10^{33} \text{ erg s}^{-1}$;
- iii) no X-ray pulsations are present and no significant X-ray outbursts are expected in the case of a coplanar circular orbit with the Be-disk;
- iv) the hot shell is convective and turbulent, therefore the observed X-ray emission lines from the optically thin plasma should be broadened up to $\sim 1000 \text{ km s}^{-1}$;
- v) the typical size of the hot shell is $\sim R_B \lesssim R_\odot$;
- vi) the cold material, such as the Be-disk in the vicinity of the hot shell, should give rise to fluorescent FeK-line;
- vii) the life-time of a NS in the propeller regime in binaries with long orbital periods can be $\sim 10^6 \text{ yrs}$, hence such systems should be observable among faint X-ray binaries in the Galaxy.

7 OBSERVED X-RAY PROPERTIES OF γ CAS CAN BE EXPLAINED BY THE PRESENCE OF A PROPELLING NEUTRON STAR

The model predictions outlined in Sect. 6 match very well the properties of γ Cas deduced from observations. We suggest that the low-mass companion of γ Cas can be a NS in the propeller stage. The NS orbits the Be-star in almost circular orbit coplanar with the Be-disk. The Be-disk is contained within the Roche lobe of the Be-star ($\sim 310 R_\odot$)¹, and the NS gravitationally captures matter from the slow Be-disk equatorial wind, which is not limited by the Roche lobe of the Be-star. The scale-height of the disk outflow in γ Cas is $H_{\text{disk}} = 0.04 R_*$ (Martin et al. 2011), comparable to the aspect ratio of the Bondi radius, which is sufficient to realize the quasi-spherical accretion. The lack of periodic pulsations, as well as properties of the hot thermal plasma measured from the analysis of X-ray observations ($kT_{\text{hot}} \sim 20 \text{ keV}$ and $n_e \sim 10^{13} \text{ cm}^{-3}$, $v_{\text{turb}} \sim 1000 \text{ km s}^{-1}$) (e.g. Lopes de Oliveira et al. 2010; Torrejón et al. 2012; Shrader et al. 2015), which challenge all previously proposed scenarios of X-ray emission from γ Cas (Smith et al. 2016), are naturally expected in a hot magnetospheric shell around a propelling NS (Eqs. 2, 8, 10 and Section 6).

The propeller model explains both the gross physical parameters of hot plasma in γ Cas and matches the properties of its X-ray

variability. Indeed, a hot convective shell above the NS magnetosphere should display the time variability in a wide range that depends on the characteristic sound speed, c_s , which is of the order of the free-fall time, t_{ff} . The shortest time-scale is $t_{\text{min}} \sim R_A/c_s \sim R_m/t_{\text{ff}}(R_m) \sim R_m^{3/2}/\sqrt{2GM} \sim$ a few seconds, while the longest time scale is $t_{\text{max}} \sim R_B/t_{\text{ff}}(R_B) \sim 10^6[s](v_0/100 \text{ km s}^{-1})^{-3} \sim$ a few days. These are indeed the typical time scales of the X-ray variability observed in γ Cas (Lopes de Oliveira et al. 2010).

Typically, Be-type stars display significant time variability in the optical that is produced by changes in the mass-loss rates due to stellar pulsations and possible viscose instabilities in the circumstellar disk (Baade et al. 2016). In complex systems consisting of a pulsating Be-star, decretion Be-disk and a NS, one can expect the characteristic time delay between any changes in the stellar mass-loss rate and Be-disk (usually observed in the optical) and the response of the hot magnetospheric shell (usually observed in the X-rays) to these changes.

The dynamics of disks in binary systems is complicated, especially in the case of large mass ratio, as in the Be+NS case (see, e.g., recent 2D-simulations D’Orazio et al. 2016). In addition, in a Be+NS system, the decretion Be-disk is subjected to a number of perturbations and resonances which truncate the outer disk edge within the Roche lobe of the Be-star (Okazaki & Negueruela 2001). The Roche lobe radius of the NS is

$$R_L(M_X)/a \approx 0.49 \left(\frac{M_X}{M_{\text{Be}} + M_X} \right)^{1/3} \approx 0.2 \quad (17)$$

where a is the binary semi-major axis, and we used $M_X/M_{\text{Be}} \approx 1/16$ for γ Cas. The characteristic time delay is then determined by the free-fall time inside the NS’s Roche lobe,

$$t_{\text{ff}}(M_X) \approx \sqrt{\frac{R_L^3(M_X)}{2GM_X}} = \frac{P_{\text{orb}}}{2\pi} \sqrt{\frac{R_L(M_X)}{2}} \sqrt{\frac{M_{\text{Be}} + M_X}{M_X}}, \quad (18)$$

where we have used 3d Kepler’s law $\omega_B^2 = G(M_{\text{Be}} + M_X)/a^3$. Plugging values for γ Cas immediately yields $t_{\text{ff}} \sim 40$ days, which is close to the time lag between optical and X-ray variability observed in γ Cas (Motch et al. 2015).

Changes in the absorption column density are also expected due to perturbations in the cold disk and wind induced by the NS on short and long time-scales (Martin et al. 2011; Smith et al. 2012; Hamaguchi et al. 2016). Note also that the single power-law spectrum $P(f) \sim 1/f$ over the wide frequency range from 0.1 Hz to 10^{-4} Hz , as derived for the X-ray time variability in γ Cas (Lopes de Oliveira et al. 2010), is common for accreting X-ray binaries and is thought to arise in turbulent flows beyond the magnetospheric boundary (Revnivtsev et al. 2009).

Future works on sophisticated multi-dimensional numeric hydrodynamic models of Be-stars, their disks and companion NSs will provide more insight into the complex interactions in such systems. Even in the non-relativistic cases of Be-binaries, the hydrodynamic models show that the shape of the disk is affected by the secondary (Panoglou et al. 2016). Such modeling is required to explain the full range of variability observed in γ Cas and its analogs.

8 γ CAS ANALOGS IN THE CONTEXT OF EVOLUTION OF MASSIVE BINARIES

During the last decade, about a dozen Be-stars sharing similar characteristics with γ Cas were discovered (Smith et al. 2016, and references therein). It became clear that γ Cas is not a peculiar object

¹ The Be-disk size in γ Cas as measured by the infrared interferometry (Gies et al. 2007) and inferred from emission lines spectroscopy (Hanuschik et al. 1988; Dachs et al. 1992) is about two times as small, apparently because these observations sample mostly the densest innermost parts of the disk-like wind outflow; millimeter photometry indeed suggests a larger disk radius, $\sim 33 R_*$, which is close to the Roche lobe size (Waters et al. 1991).

but a representative of a whole class of objects. We propose the following evolutionary scenario for γ Cas analogs.

All γ Cas-type stars were likely formed through similar evolutionary channels. Consider, for example, the standard evolutionary scenario of a massive binary system with almost equal initial masses $M_p \sim 10 - 11 M_\odot$ and $M_s \sim 8 M_\odot$ separated by 20 solar radii. After the main-sequence stage, the primary overfills its Roche lobe and transfers a significant amount of matter and angular momentum to the secondary. The hydrogen envelope of the primary is stripped off during the mass transfer to leave the naked helium-rich primary remnant with the mass $M_{He} \sim 0.1 M_p^{1.4} \simeq 3 M_\odot$. The secondary mass increases up to $M_{Be} \sim 15 M_\odot$, and the star acquires rapid rotation. Rotating at nearly break-up velocity, the secondary is now observed as an early Be-type star with the surrounding disk. Then the helium star explodes as an electron-capture SN (ECSN) and produce a NS with mass $M_X \sim 1 M_\odot$ (e.g. Postnov & Yungelson 2014; Moriya & Eldridge 2016). Supernovae of this type naturally produce NSs with low-velocity kicks (Podsiadlowski et al. 2004; van den Heuvel 2010).

After the ECSN with low kick, the newly born NS remains in the plane of the Be decretion disk and stays in an orbit with low-eccentricity $e = (M_{He} - M_X)/(M_{Be} + M_X) \sim 0.1$ but moves to a somewhat wider separation (in γ Cas the putative NS is at $\sim 35 R_*$ from the Be-star). Importantly, due to low kick velocity, the NS orbits the Be-star in the Be-disk plane. Be-stars have high dense equatorial winds, the orbital velocity of NS relative to the Be-disk wind can be low, which potentially provides an efficient quasi-spherical accretion. However, the high spin of the young NS inhibits accretion of matter captured from the low-velocity wind of the Be-star. Instead, the NS is embedded in a hot shell, which we presently observe in X-rays.

The hot shell mediates the angular momentum transfer from the NS magnetosphere and can prolong the propeller stage of the NS up to several 10^5 years or even longer. Therefore, in binaries with long orbital periods, such as γ Cas, the duration of the propeller stage can be comparable to the life-time of the Be star (see Eq. 14). Thus, a sizable fraction of Be X-ray binaries in the propeller stage, i.e. γ Cas analogs, should exist in the Galaxy, as indeed observed.

With time, the NS slows down. Once its spin period becomes such that corotation radius equals the magnetospheric radius the accretion may begin. The NS spin period reaches equilibrium (hundreds of seconds in the quasi-spherical wind, Shakura et al. (2012)) at which torques acting on the NS, on average, vanish. With the beginning of accretion, the NS will become a slowly rotating X-ray pulsar. It should remain in a circular orbit in the plane of the Be decretion disk and have a relatively large orbital separation. The observational manifestation of such post- γ Cas system is X Per – a slowly rotating X-ray pulsar at the stage of quasi-spherical settling accretion with moderate X-ray luminosity (Lutovinov et al. 2012).

9 DISCUSSION AND CONCLUSION

γ Cas and its analogs constitute a well observed and well studied class of objects. The vast literature on the subject was recently reviewed by Smith et al. (2016), and we refer the interested reader to that comprehensive review. Besides detailed multi-wavelengths observations, the three often invoked scenarios for the nature of γ Cas are also discussed in depth by Smith et al. (2016), and we only briefly repeat these scenarios here.

Chronologically, the first hypothesis explaining the enigmatic

X-ray properties of γ Cas was that of an accreting NS (White et al. 1982). Yet, the improvement in X-ray spectroscopy and timing led to the realization that the X-ray properties of γ Cas are very different from accreting NSs in other Be X-ray binaries.

A different commonly invoked scenario is the accretion onto a white dwarf (Haberl 1995; Apparao 2002). Smith et al. (2016) disfavor the white dwarf hypothesis because of the too high observed X-ray luminosity of γ Cas. Such X-ray luminosity is difficult to achieve without increasing the supply of matter from the Be-disk by discrete ejections, and these are not frequent enough. Lopes de Oliveira et al. (2006) considered accretion onto a magnetic white dwarf. Our estimates show that a propelling magnetic white dwarf as the companion in γ Cas is disfavored since, with the typical white dwarf magnetic moment of a few $\times 10^{32} - 10^{33}$ G cm³, the magnetospheric radius given the observed low X-ray luminosity would be too large (see Eq. 7) and gas temperature too low (see Eq. 10) to match the values derived from X-ray spectroscopy. Recently Hamaguchi et al. (2016) invoked the white dwarf hypothesis to explain the observed changes in the X-ray spectral hardness ratio by the presence of absorbers that occult the hot spots on the white dwarf surface. Their estimates show that the X-ray luminosity and the absorber densities can be explained using plausible assumptions about densities and velocities in the stellar wind and disk. However, the lack of coherent pulsations from the accreting white dwarf remains unexplained.

The third scenario explaining γ Cas and its analogs does not relate to binarity. Instead it suggests a magnetic star-disk interaction. In this picture, the entanglement and stretching of magnetic loops from the stellar surface with the disk magnetic field lines lead to reconnection events that accelerate particles. These electron streams bombard the stellar surface. The thermalisation leads to the X-ray emission. Albeit some estimates on the thermalisation efficiencies are made, this scenario is entirely phenomenological at present and is lacking any predictive power (Smith et al. 2016). Note that recently Schoeller et al. (submitted to A&A) attempted to detect magnetic fields in some γ Cas-analogs using spectropolarimetric observations, but no evidence for magnetic fields have been found.

In this paper we propose a novel explanation of the enigmatic class of γ Cas analogs. Using the well established physical models of propelling NSs surrounded by hot convective magnetospheric shells in wind-fed accreting systems, we derive quantitative predictions and compare them with the key observational properties of γ Cas. This comparison leads us to conclude that a propelling NS in γ Cas matches theoretical predictions very well. Moreover, the existence of young fast spinning NS companions (propellers) to early Be-stars in circular and coplanar orbits is a natural consequence of the standard evolutionary scenario of massive binary stars and ECSN models. Hence, the synergy between the stellar evolution and accretion theories predicts the existence of γ Cas and its analogs.

10 ACKNOWLEDGEMENTS

The authors acknowledge ISSI (Bern) for hospitality. We thank the anonymous referee for useful comments and suggestions that helped to improve this paper. The work of KP is supported by RSF grant 16-12-10519. JMT acknowledges the research grant ESP2014-53672-C3-3-P and LO acknowledges the DLR grant 50 OR 1508.

REFERENCES

- Apparao K. M. V., 2002, *A&A*, **382**, 554
- Arons J., Lea S. M., 1976, *ApJ*, **207**, 914
- Baade D., et al., 2016, *A&A*, **588**, A56
- Bondi H., Hoyle F., 1944, *MNRAS*, **104**, 273
- Bozzo E., Falanga M., Stella L., 2008, *ApJ*, **683**, 1031
- D’Orazio D. J., Haiman Z., Duffell P., MacFadyen A., Farris B., 2016, *MNRAS*, **459**, 2379
- Dachs J., Hummel W., Hanuschik R. W., 1992, *A&AS*, **95**, 437
- Davies R. E., Pringle J. E., 1981, *MNRAS*, **196**, 209
- Delgado-Martí H., Levine A. M., Pfahl E., Rappaport S. A., 2001, *ApJ*, **546**, 455
- Gies D. R., et al., 2007, *ApJ*, **654**, 527
- Grebenev S. A., Sunyaev R. A., 2007, *Astronomy Letters*, **33**, 149
- Haberl F., 1995, *A&A*, **296**, 685
- Hamaguchi K., Oskina L., Russell C. M. P., Petre R., Enoto T., Morihana K., Ishida M., 2016, preprint, ([arXiv:1608.01374](https://arxiv.org/abs/1608.01374))
- Hanuschik R. W., Kozok J. R., Kaiser D., 1988, *A&A*, **189**, 147
- Harmanec P., et al., 2000, *A&A*, **364**, L85
- Hong J., et al., 2016, *ApJ*, **825**, 132
- Illarionov A. F., Sunyaev R. A., 1975, *A&A*, **39**, 185
- Lattimer J. M., Prakash M., 2007, *Phys. Rep.*, **442**, 109
- Lopes de Oliveira R., Motch C., Haberl F., Negueruela I., Janot-Pacheco E., 2006, *A&A*, **454**, 265
- Lopes de Oliveira R., Smith M. A., Motch C., 2010, *A&A*, **512**, A22
- Lutovinov A., Tsygankov S., Chernyakova M., 2012, *MNRAS*, **423**, 1978
- Lutovinov A., Tsygankov S., Krivonos R., Molkov S., Poutanen J., 2016, preprint, ([arXiv:1607.03427](https://arxiv.org/abs/1607.03427))
- Martin R. G., Pringle J. E., Tout C. A., Lubow S. H., 2011, *MNRAS*, **416**, 2827
- Mason K. O., White N. E., Sanford P. W., 1976, *Nature*, **260**, 690
- Miroshnichenko A. S., Bjorkman K. S., Krugov V. D., 2002, *PASP*, **114**, 1226
- Moriya T. J., Eldridge J. J., 2016, *MNRAS*, **461**, 2155
- Motch C., Lopes de Oliveira R., Smith M. A., 2015, *ApJ*, **806**, 177
- Okazaki A. T., Negueruela I., 2001, *A&A*, **377**, 161
- Panoglou D., Carciofi A. C., Vieira R. G., Cyr I. H., Jones C. E., Okazaki A. T., Rivinius T., 2016, *MNRAS*, **461**, 2616
- Pfahl E., Rappaport S., Podsiadlowski P., Spruit H., 2002, *ApJ*, **574**, 364
- Podsiadlowski P., Langer N., Poelarends A. J. T., Rappaport S., Heger A., Pfahl E., 2004, *ApJ*, **612**, 1044
- Popov S. B., Turolla R., 2012, *Astroph.Sp.Sci.*, **341**, 457
- Porter J. M., Rivinius T., 2003, *PASP*, **115**, 1153
- Postnov K. A., Yungelson L. R., 2014, *Living Reviews in Relativity*, **17**
- Reig P., 2011, *Astroph.Sp.Sci.*, **332**, 1
- Revnivtsev M., Churazov E., Postnov K., Tsygankov S., 2009, *A&A*, **507**, 1211
- Shakura N., Postnov K., Kochetkova A., Hjalmarsdotter L., 2012, *MNRAS*, **420**, 216
- Shrader C. R., Hamaguchi K., Sturmer S. J., Oskina L. M., Almeyda T., Petre R., 2015, *ApJ*, **799**, 84
- Shtykovskiy P., Gilfanov M., 2005, *A&A*, **431**, 597
- Smith M. A., et al., 2012, *A&A*, **540**, A53
- Smith M. A., Lopes de Oliveira R., Motch C., 2016, *Advances in Space Research*, **58**, 782
- Stella L., White N. E., Rosner R., 1986, *ApJ*, **308**, 669
- Torrejón J. M., Schulz N. S., Nowak M. A., 2012, *ApJ*, **750**, 75
- Tsygankov S. S., Mushtukov A. A., Suleimanov V. F., Poutanen J., 2016a, *MNRAS*, **457**, 1101
- Tsygankov S. S., Lutovinov A. A., Doroshenko V., Mushtukov A. A., Suleimanov V., Poutanen J., 2016b, *A&A*, **593**, A16
- Tutukov A., Yungelson L., Klayman A., 1973, *Nauchnye Informatsii*, **27**, 3
- Waters L. B. F., Marlborough J. M., van der Veen W. E. C., Taylor A. R., Dougherty S. M., 1991, *A&A*, **244**, 120
- White N. E., Swank J. H., Holt S. S., Parmar A. N., 1982, *ApJ*, **263**, 277
- van den Heuvel E. P. J., 2010, *New Astron. Rev.*, **54**, 140
- van den Heuvel E. P. J., Heise J., 1972, *Nature Physical Science*, **239**, 67